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Bound excited states in ^{27}F

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Abstract

The ^{1}H(^{27}F, ^{25,26,27}F) reactions have been studied at 40 MeV/nucleon average energy using a liquid hydrogen target. For ^{25}F, ^{26}F and ^{27}F nuclei, we have observed two γ-ray peaks each originating from the decay of two bound excited states. This is the first sign of the existence of bound excited states in ^{26,27}F. The presence of a single bound excited state in ^{27}F is a clear indication of a substantial change in the structure of the fluorine isotopes approaching the neutron dripline. The proposed second excited states in ^{25,26,27}F nuclei have no counterparts in either the psd or the $sdpf$ shell model calculations suggesting the appearance of nuclear structure effects lying out of these model spaces.

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One of the most fascinating questions of nuclear structure physics is where the neutron dripline lies, and more importantly, why it is there [1,2]. In this respect, an intriguing problem is that the dripline of fluorine isotopes is located at least 6 neutrons farther than that of the oxygen isotopes [3]. The naive assumption—according to which adding a proton to the oxygen nuclei makes the $\nu d_{3/2}$ state bound—can explain the bound nature of fluorine isotopes up to ^{29}F only. To bind another pair of neutrons some kind of shell breaking mechanism like multi-particle–multi-hole excitations across major shells has to be assumed, since the last two neutrons above the $N = 20$ shell closure are unbound in the spherical limit by more than 2 MeV [4]. Neutron 2-particle–2-hole excitations across the $N = 20$ shell are well known in this region, as they form the ground state of ^{32}Mg or ^{30}Ne nuclei discussed, e.g., in [5–7]. Proton excitations across the $Z = 8$ shell have also been observed as negative parity states in lighter odd fluorine nuclei $^{17–21}$F. Whatever mechanism makes ^{31}F particle-bound; its traces should be visible in other fluorine nuclei, too. For instance, in ^{27}F the psd shell model (using the cross-shell model space connecting the $0p$ and $1s0d$ shells with perturbation of the neighboring $0s$ and $0f1p$ shells) [8], which can account for the properties of light fluorine nuclei, predicts the first excited state with spin $1/2^+$ at 2.0 MeV energy, much higher than the neutron separation energy of 1.3(4) MeV. On the other hand, some shell breaking or dripline effects (continuum coupling, enhanced pairing) [1,2,9] acting in ^{31}F can lower the energy of this state below the separation energy. According to recent Monte Carlo shell model calculations it is enough to allow for the possibility of neutron cross shell excitations to have a bound excited state in ^{27}F [4]. To explore the traces of the mechanism which is expected to be responsible for the existence of ^{31}F in lighter fluorine nuclei, and to gain more information on its properties we have searched for bound excited states in ^{27}F.

As an experimental method, we have applied the (p, p') reaction. This process is known to have a relatively large cross section and to serve as a good tool for hunting excited states. In spite of its strong advantages, this method has rarely been used in the past for exploratory works since the proton detection required a thin target, resulting in low yields [10–12]. Combining the method with γ-ray spectroscopy, thick targets can be employed allowing for lower intensity radioactive beams [13]. Choosing liquid hydrogen as a target material, we gain a large number of target nuclei compared to solid targets of the same thicknesses making this method suitable for application with radioactive beams of the order of magnitude of 0.2 particle/s (pps) intensity. [14]. Our study was based on these two pioneering works.

The experiment was carried out at the RIKEN Accelerator Research Facility. A 94 MeV/nucleon energy primary beam of ^{40}Ar with 60 pnA intensity hit an ^{181}Ta production target of 0.5 cm thickness. The reaction products were momentum and mass analyzed by the RIPS [15] fragment separator. An aluminum wedged degrader of 221 mg/cm^2 was used at the momentum dispersive focal plane (F1) for purifying the constituents. The secondary beam included neutron-rich O, F, Ne and Na nuclei with $A/Z \approx 3$. The fragment separator was operated at its full 6% momentum acceptance to achieve as high beam intensities as possible. The total intensity was about 100 pps, while the fraction of individual isotopes varied in the range of 1–10% having a ^{27}F intensity of 4 pps on average. The identification of incident beam species was performed event by means of energy loss, time-of-flight (TOF) and magnetic rigidity $(B\rho)$ [3]. The ^{27}F particles could be fully separated from other nuclei. The position of the fragments at F1 was measured determining the $B\rho$ values by a parallel plate avalanche counter (PPAC). It had a sensitive area of 15×10 cm^2 which covered the total momentum range of the secondary beam. Two plastic scintillators of 1 mm thickness were placed at the first and second focal planes (F2 and F3) to measure the TOF. One silicon detector with thickness of 0.35 mm was inserted at F3 for energy loss determination. The secondary beam was transmitted to a liquid hydrogen target [16] of 30 mm diameter at F3. The thickness of the secondary target was 24 mm and its entrance and exit windows were made of 6.6 μm Aramid foil. The average areal density of the hydrogen cooled down to 22 K was 210 mg/cm^2. The mean energy of ^{27}F isotopes was calculated at 39.6 MeV/nucleon from the incident energy of 49.6 MeV/nucleon and the energy loss in the target. The position of the incident particles was determined by two PPACs placed at F3 upstream of the target. The beam spot size was 24 mm both in horizontal and vertical directions. The scattered particles

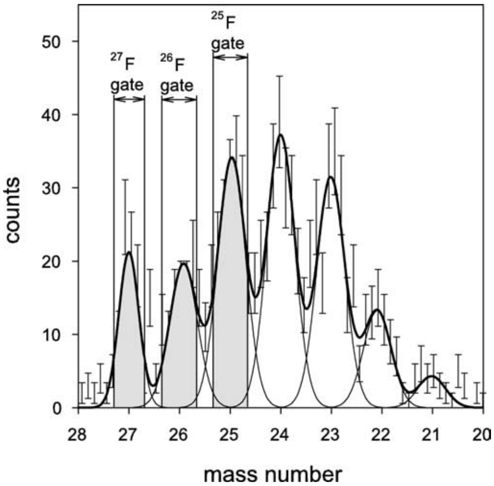

Fig. 1. Separation of fluorine isotopes using ΔE–E information in the silicon telescope.

were detected and identified by a PPAC and a silicon telescope located about 80 cm downstream of the target. The telescope consisted of three layers of Si with thicknesses of 0.5, 0.5 and 1 mm. Each layer was made of a 2×2 matrix of detectors the active area of which was 48×48 mm^2. The inelastically scattered ^{27}F particles stopped in the second and third layers. The Z identification was performed by TOF-energy loss method where the TOF was taken between the secondary target and the PPAC. In this way, we could gate out, e.g., the different Ne isotopes emerged in the liquid hydrogen target by ^{1}H(^{27}F,$^{28-x}$ Ne) $\times\, n$ reactions. Isotope separation was carried out among the different fluorine isotopes by use of the ΔE–E method. The particle spectra are dominated by the beam particles. Requiring coincidence with γ rays, we could eliminate the beam making the ΔE–E method sensitive enough. It is demonstrated in Fig. 1 where the linearized mass spectrum of fluorine isotopes is shown for one segment of the 2×2 matrix Si-telescope produced by adding the events with ^{27}F, ^{26}F and ^{25}F incident beams. The linearization of the ΔE–E curves in each detector was made by second degree polynomial functions. It is clearly seen that ^{27}F nuclei represent a distinct peak and they are well separated from other products emerged by neutron removal reactions in the liquid hydrogen target.

To detect the de-exciting γ rays emitted by the inelastically scattered nuclei the DALI2 setup including 146 NaI(Tl) scintillator detectors [17] surrounded the target. The energy calibration of the setup was made by standard ^{22}Na, ^{60}Co and ^{137}Cs radioactive sources. The intrinsic energy resolution of the array was 10% for a 662 keV energy γ ray. Fig. 2 plots the Doppler-corrected γ ray spectra for ^{27}F (a), ^{26}F (b) and ^{25}F (c) nuclei, which were produced putting an additional gate on the time spectra of the NaI(Tl) detectors selecting the prompt events and subtracting the random coincidences. The typical efficiency of the NaI(Tl) array was around 25% for 700 keV γ rays with Lorentz boost.

First, the positions of the peak candidates (500, 750, 1200 keV for ^{27}F, 470, 660, 1300 for ^{26}F, 730, 1000, 1350, 1750 keV for ^{25}F) and their uncertainties were determined by fitting the spectra with Gaussian functions and smooth exponential backgrounds. During the fitting process the widths of the peaks were fixed to the expected values including the intrinsic resolution and Doppler effect. After the peak positions have been determined they were fed into the detector simulation software GEANT4 [18] and the resultant response curves plus smooth polynomial backgrounds were used to analyze the experimental spectra in terms of the significance of the peaks by taking the 2σ level as a criterion. According to this, there are two significant peaks at 727(22) and 1753(53) keV in the ^{25}F spectrum (Fig. 2(c)). Their existence is also supported by the preliminary results obtained from an experiment using γ ray spectroscopy following projectile fragmentation [19]. In the ^{26}F spectrum (Fig. 2(b)), two peaks were found at 468(17) and 665(12) keV. There are indications on the existence of the latter one from another preliminary report on a recent experiment also using projectile fragmentation at GANIL [20]. The ^{27}F spectrum (Fig. 2(a)) also shows two peaks at 504(15) and 777(19) keV. (Note that the area of the 1753 keV peak in ^{25}F and that of the 468 keV peak in ^{26}F exceed the 2σ threshold level while the 1200 keV peak candidate in ^{27}F is just below this threshold. Therefore, the latter one was not adopted.) The confidence of the significant peaks is summarized in Table 1. The quoted uncertainties of the peak positions are the square roots of the sum of the squared uncertainties including two main errors namely the statistical one and the one due to Doppler correction. For example, the typical values of these errors for the 777 keV peak are 18 keV (statistical) and 6 keV (Doppler correction). The presence of two γ rays is a

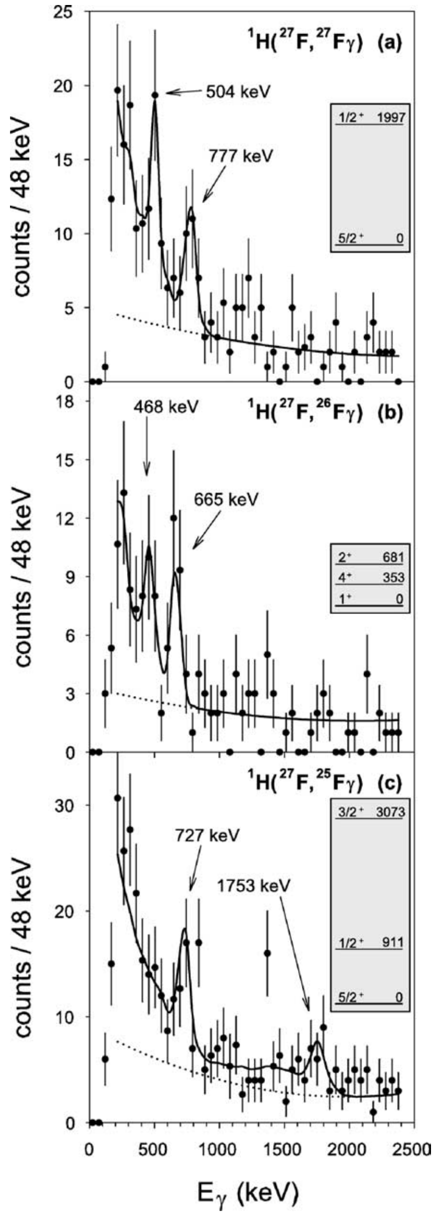

Fig. 2. Doppler-corrected spectra of γ rays emerging from ^{1}H(^{27}F, ^{27}F) (a), ^{1}H(^{27}F, ^{26}F) (b) and ^{1}H(^{27}F, ^{25}F) (c) reactions. The solid line is the final fit including the spectrum curves from GEANT4 simulation and additional smooth polynomial backgrounds plotted as separate dotted lines for each nucleus. The insets in gray boxes show the *psd* shell model predictions [8].

clear sign for the existence of two bound excited states which can be obtained by placing the γ transitions either parallel or in a cascade in each of the ^{25,26,27}F nuclei. None of these states has been reported previously.

Table 1
Confidence of the significant peaks in ^{25,26,27}F

Peak position	Confidence
727(22) keV (^{25}F)	2.4σ
1753(53) keV (^{25}F)	2.3σ
468(17) keV (^{26}F)	2.2σ
665(12) keV (^{26}F)	3.8σ
504(15) keV (^{27}F)	2.4σ
777(19) keV (^{27}F)	3.0σ

The experimental data can be compared with the predictions of the shell model calculations in spite of the ambiguity in the level schemes. The *sd* shell model [21] predicts the ground state of ^{25}F to be $5/2^+$, followed by a $1/2^+$ state at 911 keV and a $3/2^+$ one at 3373 keV. In ^{26}F, the members of the $\pi d_{5/2}\nu d_{3/2}$ multiplet give the lowest energy states starting with the 1^+ ground state and followed by the 2^+ at 681, the 3^+ at 1604 and the 4^+ state at 353 keV. In ^{27}F, a $5/2^+$ ground state is expected with the $1/2^+$ state as the first excited state at 1997 keV as mentioned earlier. Comparing the experimental data with these predictions, it is clearly seen that the energy of the 727 keV γ ray of ^{25}F and that of the 665 keV one in ^{26}F is fairly close to the predicted energies of the $1/2^+$ state in ^{25}F, and the 2^+ state in ^{26}F, respectively, and can be assigned to the decay of these states. (We note that the 468 keV γ ray in ^{26}F cannot correspond to the decay of the first excited state expected by the shell model at about the same energy, since the predicted transition from a 4^+ to a 1^+ state must have an M3 character having too long lifetime to be observed in the present experiment.) On the other hand, both levels of ^{27}F and the second excited states of ^{25,26}F appear at too low energies independently whether they are constructed by placing the γ rays parallel or in cascade.

Extending the model space to the *sdpf* shells which may allow for the breakdown of the $N = 20$ shell closure [22], a lowering to 1.1 MeV of the $1/2^+$ excited state is calculated in ^{27}F [23]. Although an excited state with a similar energy can be constructed by placing the two γ rays of ^{27}F on top of each other, on the basis of the expected decay properties, a state directly feeding the ground state is a more probable candidate for the spin 1/2 state. In spite of the ~ 300 keV energy difference, the 777 keV transition may be a reasonable candidate for the decay of the $1/2^+$ state of the *sdpf* shell model prediction. Thus, by allowing for breakdown of the $N = 20$ neutron shell closure, half of the experimental results, namely the existence of the γ ray peaks with 700 keV energy in all the ^{25,26,27}F nuclei, may be explained.

The large energy deviation between at least one of the predicted and observed excited states suggests that these states intrude from a configuration outside of the model space, or the predicted energies strongly deviate from the reality due to some additional correlations not included in the models.

We consider the possibility that the additional low energy states can be interpreted as $1/2^-$ intruder configuration. Indeed, in ^{17,19,21}F nuclei, the three lowest lying levels observed are the $5/2^+$, $1/2^+$ and $1/2^-$ states. Note that the *sdpf* shell model calculation does not include the proton *p*–*sd* shell particle–hole excitation. On the other hand, the *psd* shell model describes well the low energy negative parity excitations in the lighter fluorine nuclei however the treatment of the neutron *fp* shells is missing. Although none of the shell model calculations predicts a low-lying negative parity state, it would be worth performing theoretical investigations to check whether the simultaneous and correlated proton and neutron excitations across the $Z = 8$ and $N = 20$ shell closures is a possible source of the intruder states observed.

Finally, we analyze the (p, p') excitation probabilities of the states in terms of the collective deformation model. The experimental cross sections for the γ ray transitions are $\sigma(504\ \text{keV}) = 11.0 \pm 5.0$ mb and $\sigma(777\ \text{keV}) = 18.0 \pm 6.0$ mb. The main sources of errors quoted are NaI(Tl) array efficiency ($\approx 10\%$), target thickness ($\approx 10\%$) and statistical one ($\approx 30\%$). The “deformation” parameters can be obtained by fitting distorted-wave calculation results to the experimental cross sections following the above scenario, i.e., assuming a level scheme of ^{27}F with a spin $5/2^+$ ground state, a $1/2^+$ excited state at 777 keV, and a $1/2^-$ state at 1281 keV. In the calculations, the standard collective form factors were applied and the global phenomenological parameter set CH89 proposed in [24] was employed for the optical potential. The “deformation” parameters deduced in this way are $\beta_2 = 0.34 \pm 0.2$ if a $5/2^+ \rightarrow 1/2^+$ quadrupole transition is assumed while an octupole $\beta_3 = 0.7 \pm 0.2$ deformation parameter can be assigned to the $5/2^+ \rightarrow 1/2^-$ transition from the present experiment. (The M2-type excitation should be much suppressed.) The β_2 parameter has too large uncertainty to conclude whether the nucleus is nearly spherical as predicted by the *sdpf* shell model [4], or deformed as ^{32}Mg lying in the island of inversion. The β_3 parameter is larger than (but consistent within the errors with) the relatively large octupole deformations found in this nuclear region associated with large quadrupole deformations ($\beta_3 = 0.3$–0.5 for ^{18,20}O and ^{20}Ne) ensuring a large transition probability. Thus, the obtained transition probabilities do not contradict to the assumption of the existence of a deformed $1/2^-$ state in ^{27}F.

Summarizing our results, we have searched for bound excited states in ^{27}F by use of the (p, p') process in inverse kinematics. We observed two γ-ray lines in all the ^{25,26,27}F isotopes, and assigned them to decays of two excited states each observed for the first time. The existence of the first excited states in ^{25,26}F can be explained by the traditional shell model. A bound excited state in ^{27}F is predicted by breaking up the $N = 20$ shell [4]. The energy of the second excited state in ^{25,26}F and the resence of an additional bound state in ^{27}F cannot be explained by the available theories. This fact suggests that some additional effects are not considered in the models, e.g., simultaneous, correlated proton–neutron cross shell excitations may play a significant role in the structure of heavy fluorine isotopes. Similar effects can also contribute to the bound nature of ^{31}F.

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